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Title: The road goes ever on

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The road goes ever on

S. Mosby
P-27: LANSCE Weapons Physics

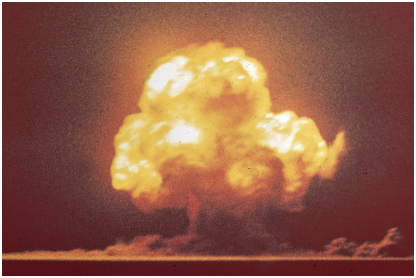
October 2, 2019

NSCL/FRIB Nuclear Science Seminar

Stuff I'll talk about

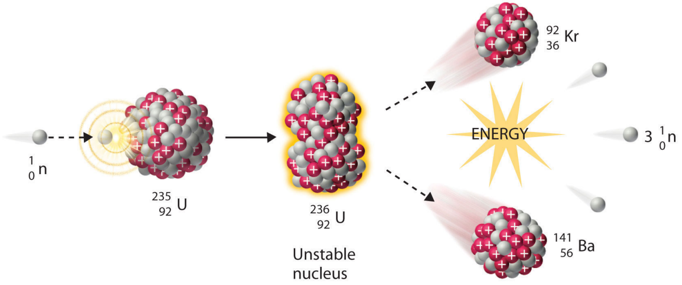
- **Applications-driven motivation and facility boundary conditions**
- Experimental mindset: SPIDER example
- Walking toward MORD0R: DANCE example
- MORD0R concept

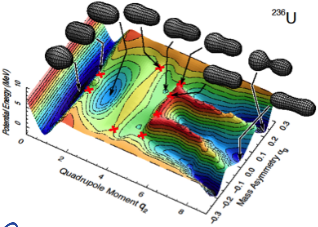
Why does LANL care about nuclear physics?



- Successful test July 16, 1945
- ...maybe we need some nuclear physics
- We want to understand reactions e.g. fission

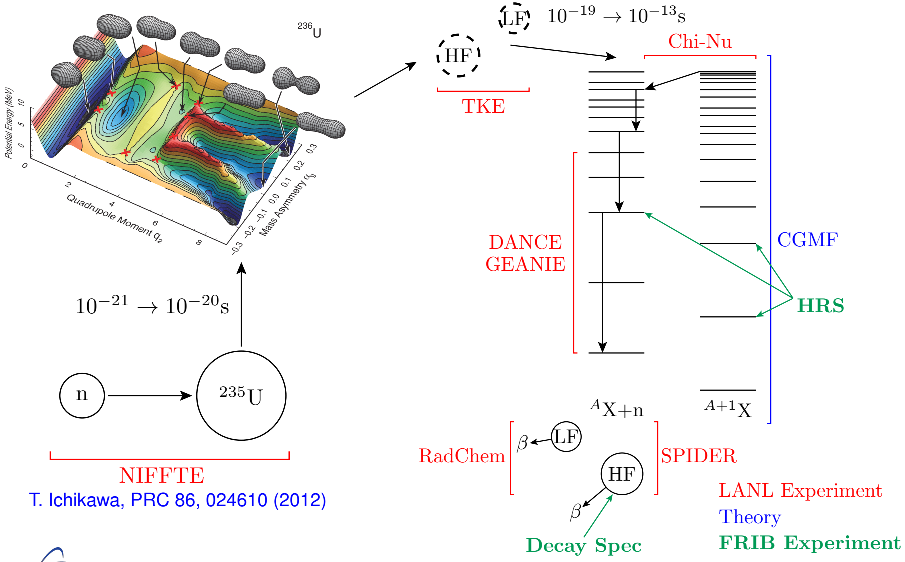
So what is nuclear fission?





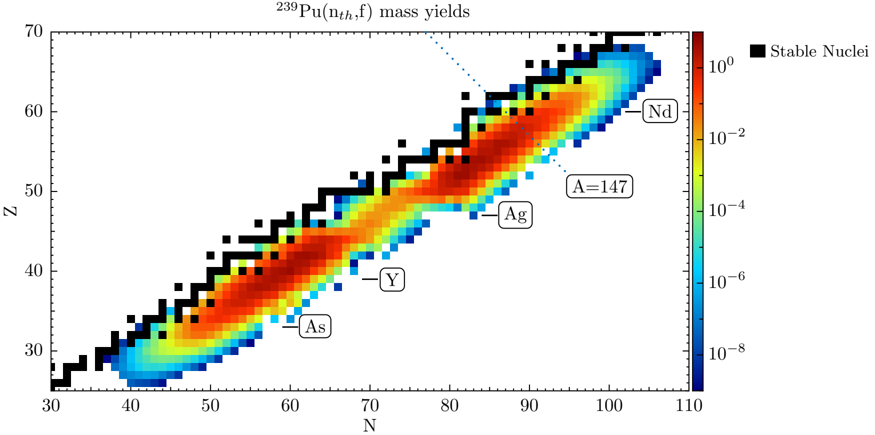
1. Incident neutron excites nucleus to "fission barrier" (10^{-20} s)
2. Nucleus evolves to scission (10^{-20} s)
3. Fragments accelerate away (10^{-19} s)
   - $\geq$1000 resulting mass combinations(!)
4. Neutrons, γ-rays emitted (10^{-17} - 10^{-13} s)

...and how do we actually study it at LANL?



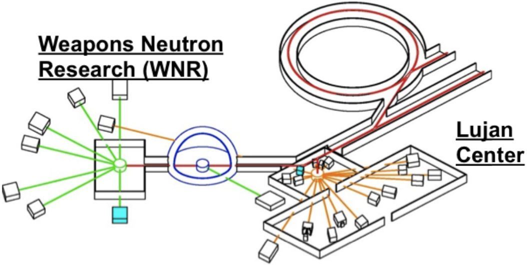
T. Ichikawa, PRC 86, 024610 (2012)

We need other reactions too



- Fission produces neutrons as well as hundreds of daughter nuclei
- The distribution of these “exhaust fumes” can be relevant for applications
- The **production** and **evolution** of these fission fragments must be understood - need e.g. (n,2n), (n,γ) reaction rates

Boundary condition: LANSCE as a capability



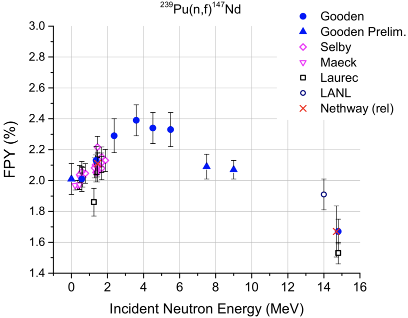
- 1/2 mile long LINAC drives 800 MeV proton beam
- Neutrons produced by spallation (smash protons into some material)
- Time of flight “white source” - shape measurements are good
- Machine can be flexible w/ pulse structure, where beam goes pulse to pulse

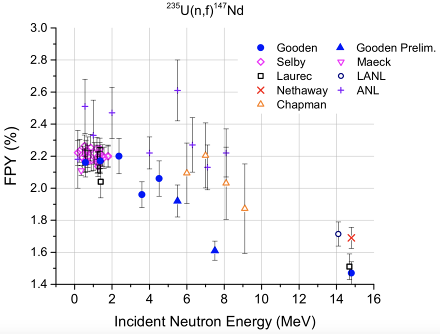
Stuff I'll talk about

- Applications-driven motivation and facility boundary conditions
- **Experimental mindset: SPIDER example**
- Walking toward MORD0R: DANCE example
- MORD0R concept

...so what makes a meaningful experiment?

Example physics case: fission product yields (FPY)



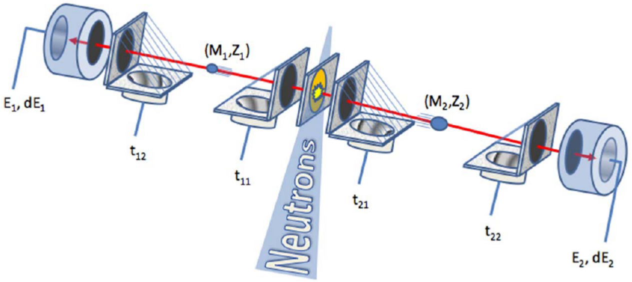


- Scarce, dated, or discrepant data is a challenge for evaluation
- Most data is for **cumulative** (β-delayed) not **independent** (prompt)
- We want the independent FPY curve from $<$1 MeV to 20 MeV

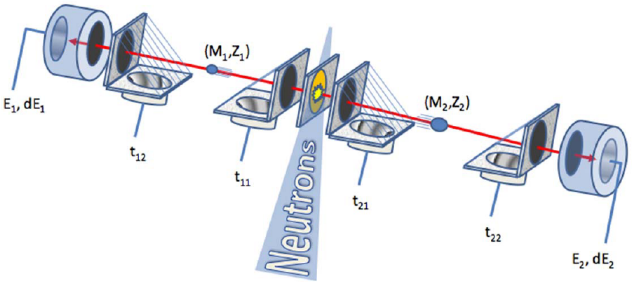
M. Gooden et al., EPJ Conferences **146**, 04024 (2017)

A suckless approach to mass measurements

- Options for mass measurements:
  - **Magnetic Spectrometer**: Lohengrin at ILL has great resolution, impractical efficiency for our interests
  - **2E**: use TKE chamber and conservation of momentum to infer masses with great efficiency, terrible resolution
  - **2E,2V**: measure velocities and energies of fission fragments to achieve “good enough” resolution and efficiency



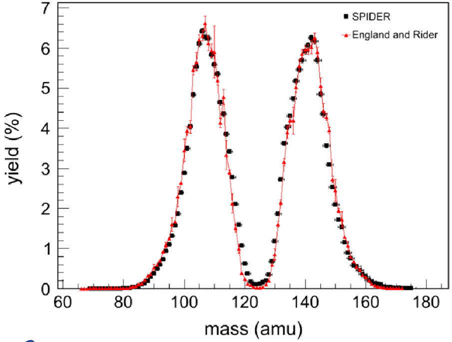
Example: SPIDER as currently developed



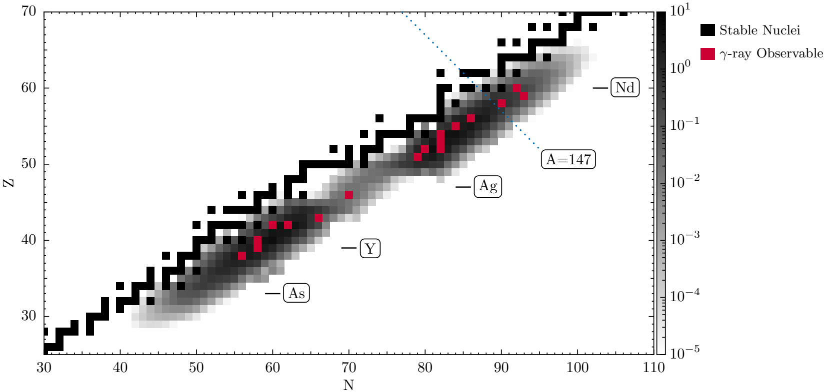
- "2E-2v" approach: $E = \frac{1}{2}mv^2 \rightarrow m = \frac{2E}{v^2}$
- Measure velocity with MCPs, energy with ion chambers.
- Multiple spectrometer arms to increase efficiency.
- Objective: $\leq$ 1 AMU mass resolution, $\sim$1 % efficiency.

What is the uncertainty of your uncertainty?

- Recent projects with close connection to evaluation community (e.g. Chi-Nu) have demonstrated the need to rigorously evaluate uncertainties.
- Applied to SPIDER: ability to construct and monitor the mass response function will dictate our ultimate uncertainty.
- Want to measure a fundamentally smooth physics quantity with both high resolution and high precision - how to know we've succeeded?



Using γ-rays to tag nuclei



- Criteria: separable γ-ray lines with reasonable feeding (look at a lot of even-even nuclei).
- Ability to extend to edges of mass peaks will depend on design details, practicalities of run time.

...so what have we learned?

- Interaction with detector physics and technology
  - All the easy measurements are (always) done
  - New measurements are always at the limit of something (e.g. detector tech)
- Our ideal error bar is:
  1. Small enough to matter
  2. Understood enough to be believed

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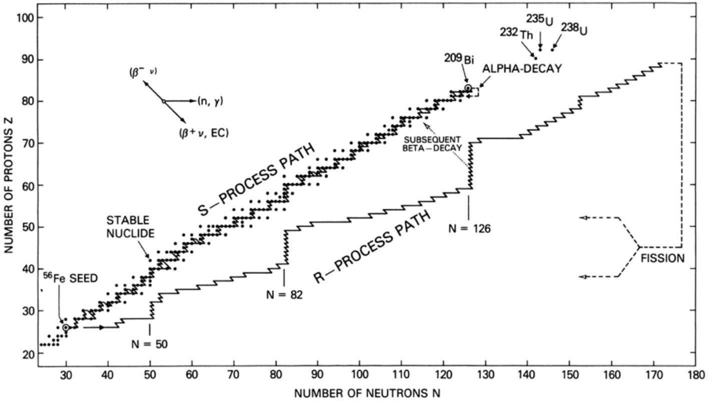
- **Walking toward MORD0R: DANCE example**
- MORD0R concept

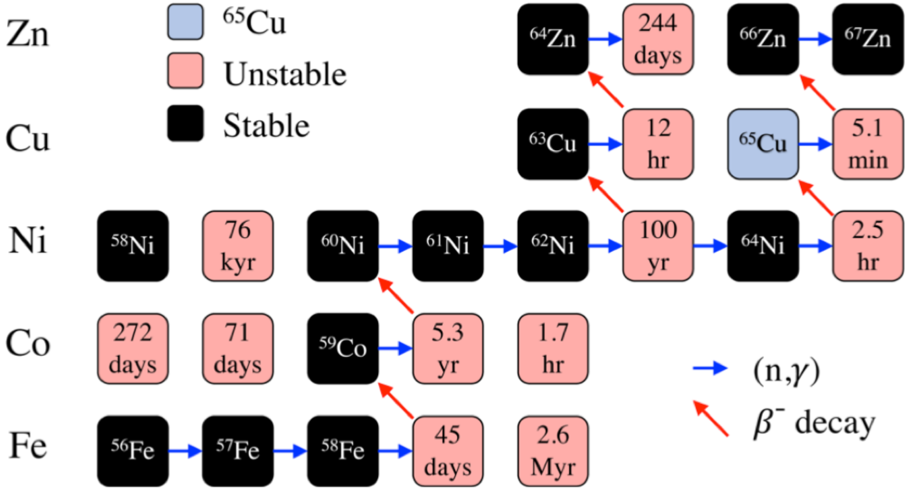
A brief astrophysical aside

- **Understanding of the origin of the elements in the observable universe is important**
  – Most of the isotopes of elements heavier than iron are created via the slow (s-process) and rapid (r-process) neutron capture processes



Rolfs, C. E., & Rodney, W. S. (1988). *Cauldrons in the cosmos: Nuclear astrophysics*. Chicago: University of Chicago Press.

Where ^{65}Cu sits



C. J. Prokop

So what's the reaction rate?

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Neutron total cross sections and resonance parameters of $^{63}_{29}\mathrm{Cu}$ and $^{65}_{29}\mathrm{Cu}$. I

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Acc

Neutron capture cross sections for the weak s process in massive stars

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$^{63}\mathrm{Cu}(n,\gamma)$ cross section measured via 25 keV activation and time of flight

M. Weigand, C. Beinrucker, A. Couture, S. Fiebiger, M. Fonseca, K. Göbel, M. Heftrich, T. Heftrich, M. Jandel, F. Käppeler, A. Krása, C. Lederer, H. Y. Lee, R. Plag, A. Plompen, R. Reifarth, S. Schmidt, K. Sonnabend, and J. L. Ullmann

Phys. Rev. C **95**, 015808 – Published 31 January 2017

1977

^{63}Cu MACS = 94 ± 10 mb

^{65}Cu MACS = 41 ± 5 mb

2008

^{63}Cu MACS = 55.6 ± 2.2 mb

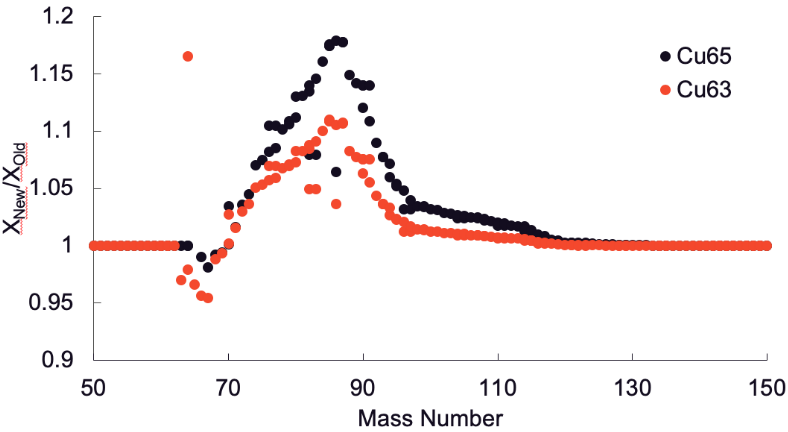
^{65}Cu MACS = 29.8 ± 1.3 mb

2017

^{63}Cu MACS = 84 ± 7 mb

You really do want to know the right answer

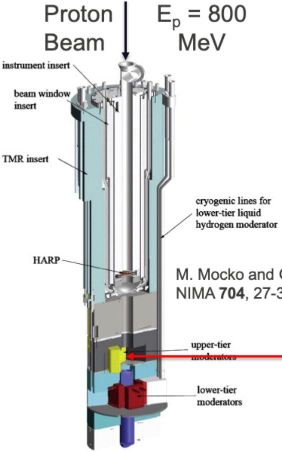
Effect of changing both cross sections (independently) by a factor of 1.5



http://exp-astro.physik.uni-frankfurt.de/netz/

C. J. Prokop

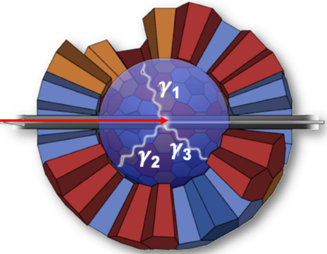
How a DANCE measurement works



M. Mocko and G. Muhrer, NIMA **704**, 27-35 (2013)

- **DANCE is a γ-ray calorimeter**
  - **$E_n = 0.5m_n(L/TOF)^2$**
  - **$E_{Sum} = E(\gamma_1) + E(\gamma_2) + E(\gamma_3) + \ldots + E(\gamma_n)$**
  - **M_{Cr} is the observed crystal multiplicity**

https://t2.lanl.gov/fiesta2014/images/dance.png

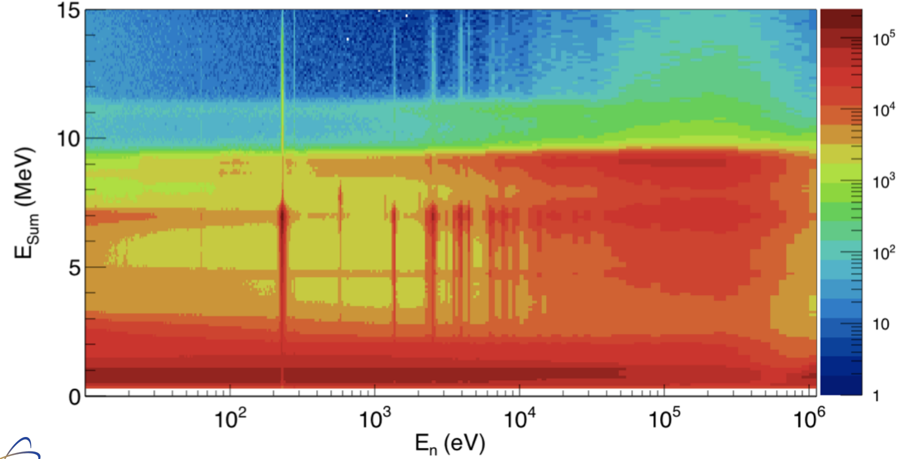


L = 20.28m

C. J. Prokop

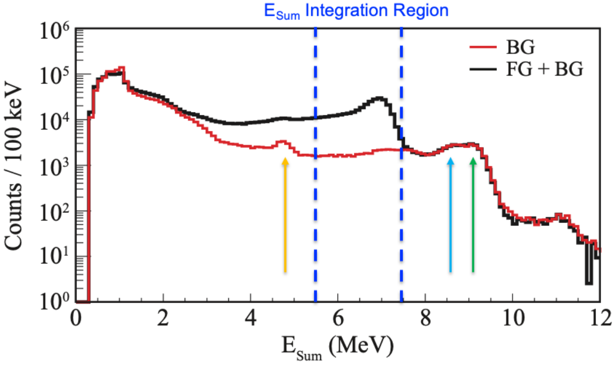
What data looks like

- E_n is the neutron energy determined via Time-Of-Flight
- E_{Sum} is the total energy of all γ rays in a given event
- Binning is a “Constant Counts Binning”



Backgrounds

- **Primary source of background in DANCE originates from scattered neutrons capturing inside the BaF_2 crystals**
- **^{208}Pb Sample used for characterization**
  - Low capture and large scatter cross section
  - Low 3.94-MeV (n,γ) Q-value



Abundances and (n,γ) Q-Values of of Stable Barium Isotopes

^{130}Ba (0.1%) – 7.49 MeV

^{132}Ba (0.1%) – 7.18 MeV

^{134}Ba (2.4%) – 6.97 MeV

^{135}Ba (6.6%) – 9.11 MeV

^{136}Ba (7.9%) – 6.91 MeV

^{137}Ba (11.2%) – 8.61 MeV

^{138}Ba (71.7%) – 4.72 MeV

Results

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Neutron total cross sections and resonance parameters of $^{63}_{29}\mathrm{Cu}$ and $^{65}_{29}\mathrm{Cu}$. I

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$^{63}\mathrm{Cu}(n,\gamma)$ cross section measured via 25 keV activation and time of flight

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CB10596 - Measurement of the $^{65}\mathrm{Cu}(n,\gamma)$ cross section using DANCE

1977

^{63}Cu MACS = 94 ± 10 mb

^{65}Cu MACS = 41 ± 5 mb

2008

^{63}Cu MACS = 55.6 ± 2.2 mb

^{65}Cu MACS = 29.8 ± 1.3 mb

2017

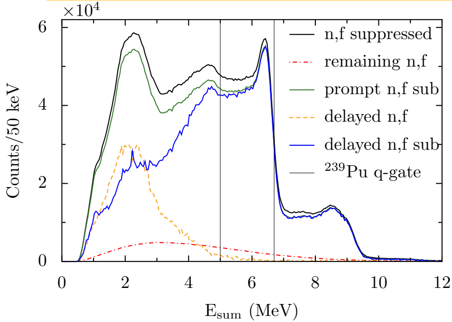
^{63}Cu MACS = 84 ± 7 mb

2019

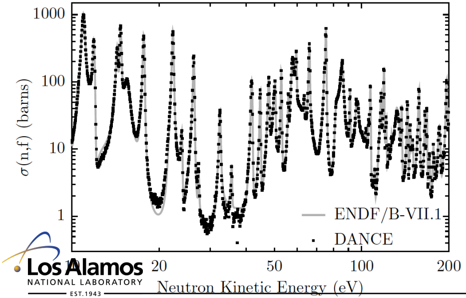
^{65}Cu MACS = 37.0 ± 3.3 mb

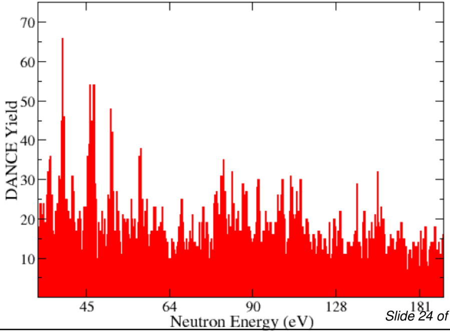
C. J. Prokop et al, PRC **99**, 055809 (2019)

How to break DANCE: radioactive targets

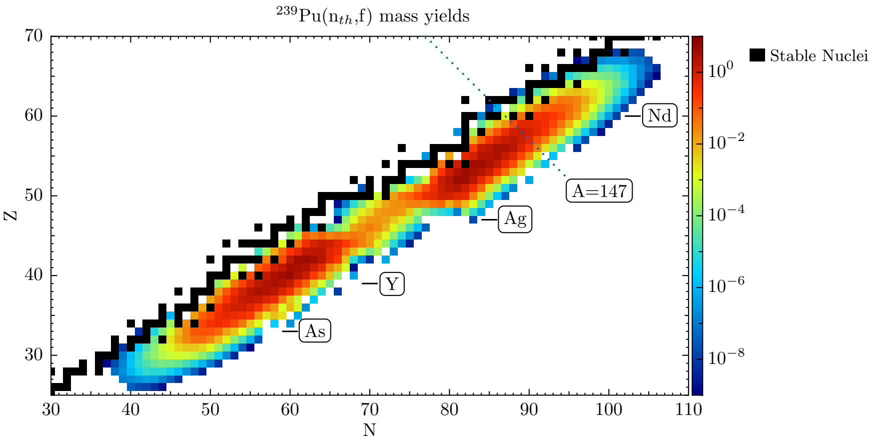


- γ-rays from decays overwhelms physics signal
- Detector response breakdown from pileup, ultimate degredation of observables (e.g. resonances)

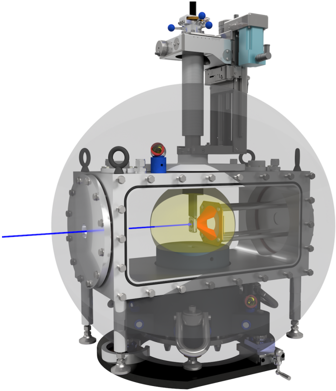


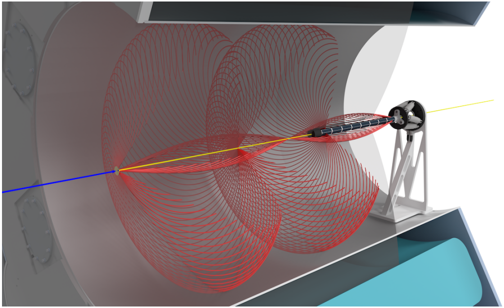


Remember: we care about unstable nuclei



The current state of the art: LENZ example

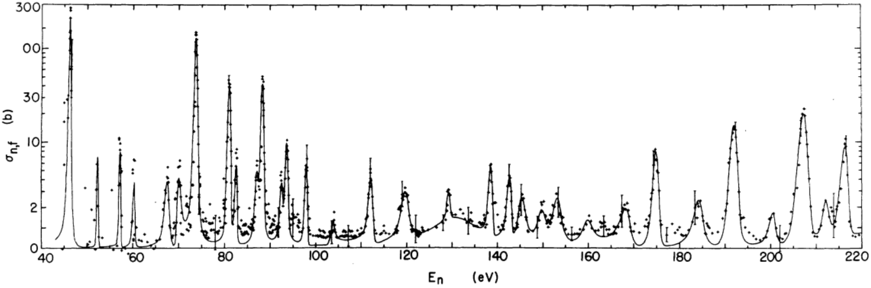




- LENZ does (n,p), (n,α) - radiation field from β-unstable nuclei ultimately can kill detectors (analagous to DANCE)
- Pursuing solenoid spectrometer to eliminate β, provide shielding from direct γ field
- Potential for $\sim$week half lives

H. Y. Lee and B. DiGiovine 2019

...when you get ***really*** desperate: ^{237}U(n,f)



- J. H. McNally et al, PRC **9**, 717 (1974) measured resonances in ^{237}U(n,f) ($T_{1/2}$ 6.7 d)
- "The use of an underground nuclear explosion as an intense neutron source for time-of-flight cross-section mesurements has been described... The advantages of this method over more customary laboratory sources lie in the extreme intensity of the neutron beam."
- Irradiated ^{236}U at ORNL to 1.9% ^{237}U, separated at LANL to $\sim$70% purity for the experiment

Stuff I'll talk about

- Applications-driven motivation and facility boundary conditions
- Experimental mindset: SPIDER example
- Walking toward MORD0R: DANCE example
- **MORD0R concept**

What I *won't* talk about

- DICER at LANSCE, β-Olso / Oslo, surrogates... are all indirect techniques to *constrain* capture rates. Right now we're talking about direct measurements.

How to build a neutron target (and why it helps)

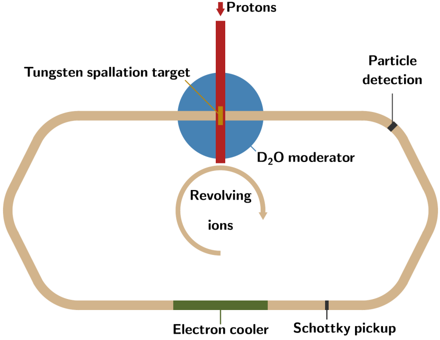


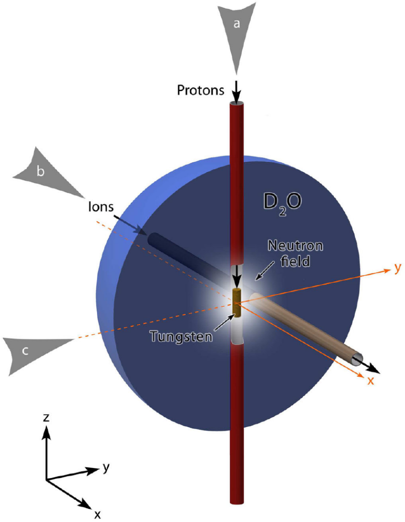
TABLE III. Neutron density for the simulated setup at two facilities: 100 μA proton beam with 800 MeV and the small tungsten target (LANL), as well as 3×10^{12} protons/s with an energy of 20 GeV and the large tungsten target (CERN), see Eq. (2).

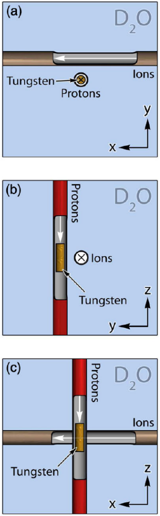
	Neutron density (cm^{-2})	
Moderator radius (m)	LANL	CERN
0.0	1.6×10^6	8.7×10^3
0.5	2.6×10^9	1.6×10^8
1.0	5.2×10^9	3.6×10^8
2.0	7.8×10^9	5.4×10^8

R. Reifarth et al., Phys. Rev. Accel. Beams **20**, 044701 (2017)

Need $\sim 10^{10}$ n/cm^2 for this to work, potentially do (n,γ), (n,2n), (n,Z)

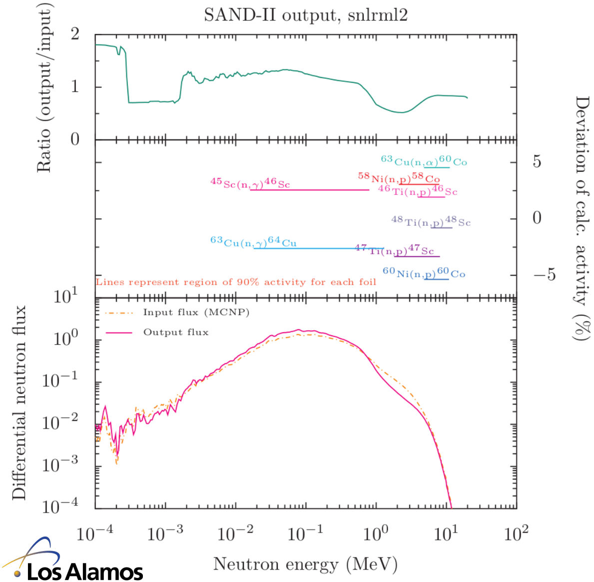
How to make a ball of neutrons





- Neutron production via spallation
- Large size limit: D_2O wins as a moderator
- Heavy ion beam line penetrates moderator assembly
- Proton beam, heavy ion ring not intersecting

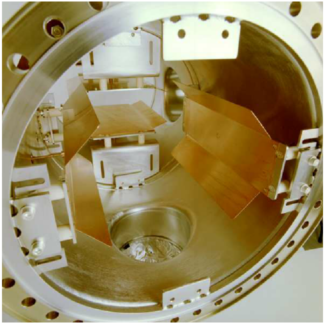
Neutron target monitoring

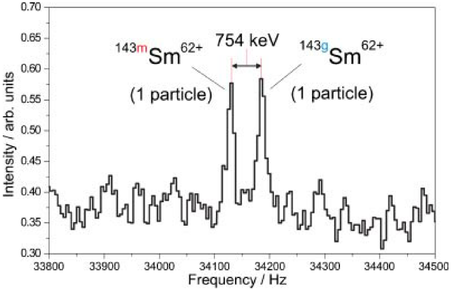


- Neutron spectrum unfolding from activation foils is used for e.g. critical assembly experiments
- Good to few percent, precedent for diagnosing issues with past experiments

M. Mosby et al., LA-UR-15-24181

How to detect reactions without detecting reactions

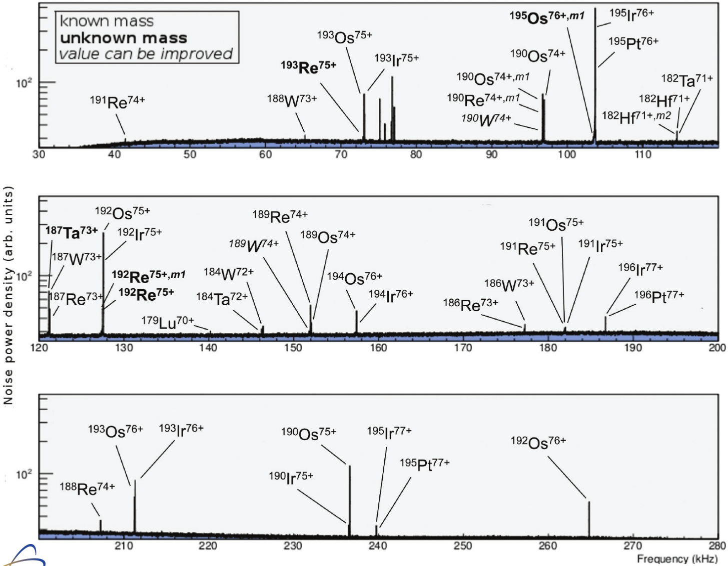




- Schottky pickup has been used as a beam diagnostic, can observe individual ions
- Digitize time-domain pickup, analyze in fequency domain offline

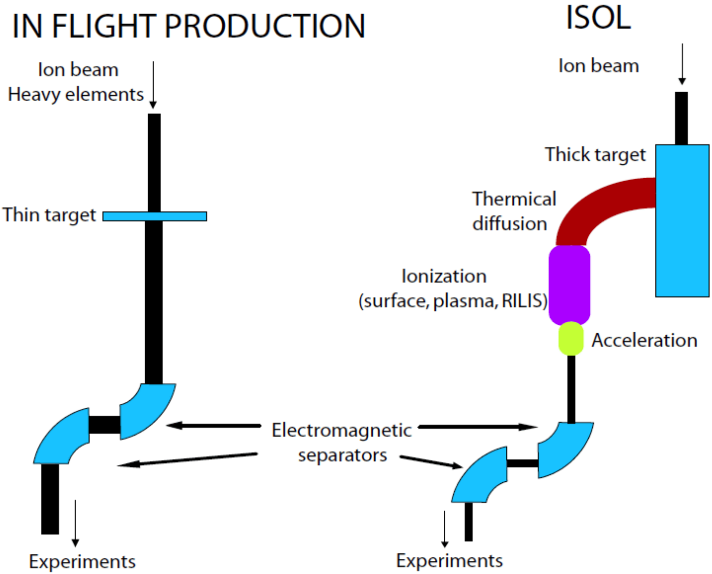
B. Franzke et al., Mass Spec. Rev. **27**, 428 (2008)

Many beams can be in ring simultaneously



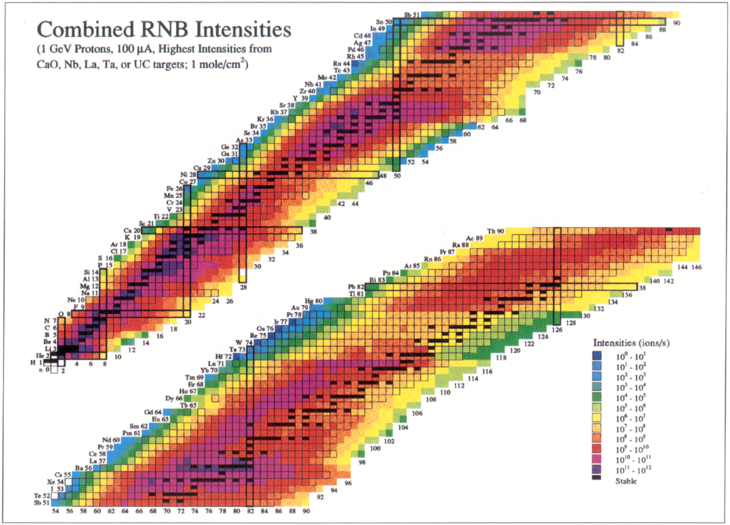
D. Shubina et al., PRC **88**, 024310 (2013)

How to make low-energy RIBs



S. Naimi (2010)

Yeah, ISOL could work pretty well

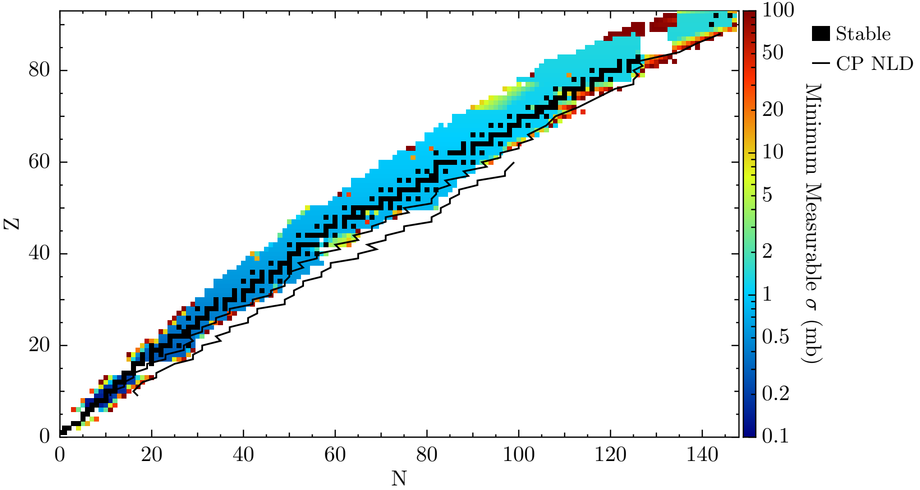


"The IsoSpin Laboratory" LALP 91-51

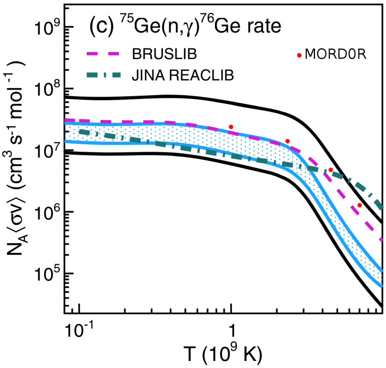
...why not do this at LANSCE?

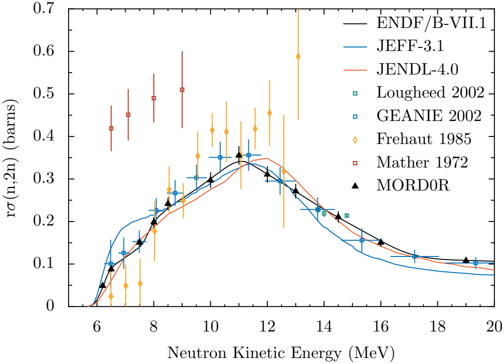
- Proton beams are needed for both RIB and neutron production
  - ISOL is the obvious choice for this application
- Machine can deliver the necessary beam power - 1 mA “back in the day”

Predicted reach using LANSCE accelerator complex



What data could look like

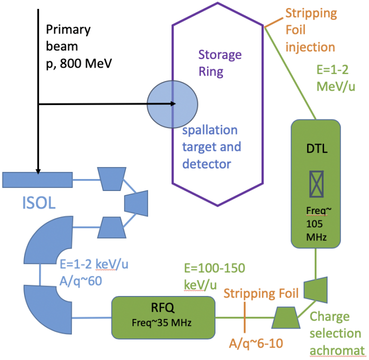




- A. Spyrou et al., PRL **113**, 232502 (2014) $T_{1/2} = 83\ m$
- Size of red dots indicates uncertainty estimate for this method

Where we are, where we are going

- Workshop "Opportunities with a Neutron Target Facility" August 19 - 20
  - 40 people, peer review of concept
  - Positive reaction, high TRL solutions exist for each subsystem
  - Outcome: the concept is feasible. Go work out the details
- Working with AOT-AE to sort funding for next steps
  - Integration with LANL Accelerator Strategy
  - Exploration of subsystem integration, staging options
- Investigating impact - building collaboration with XTD



Conclusions

- Neutron-induced reactions are a topic of general interest in nuclear technology and nuclear astrophysics
- The details matter when attempting to make an impactful measurement (and there are many left to do)
- Direct measurements for neutron-induced reactions on short-lived nuclei are currently impossible due to technical limitations of the current techniques
- It appears possible to directly measure neutron-induced reaction rates for a large swath of the relevant nuclei by combining existing beam and detector technologies in a new way.
- We are actively investigating this idea at LANSCE

Acknowledgements

DANCE:

C. J. Prokop

A. Couture

G. Rusev

J. Ullmann

SPIDER

J. Winkelbauer

D. Connolly

MORD0R:

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M. Mosby

N. Moody

D. Gorelov

J. Guzik

M. White

R. Reifarth (Frankfurt)

Y. Litvinov (GSI)

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